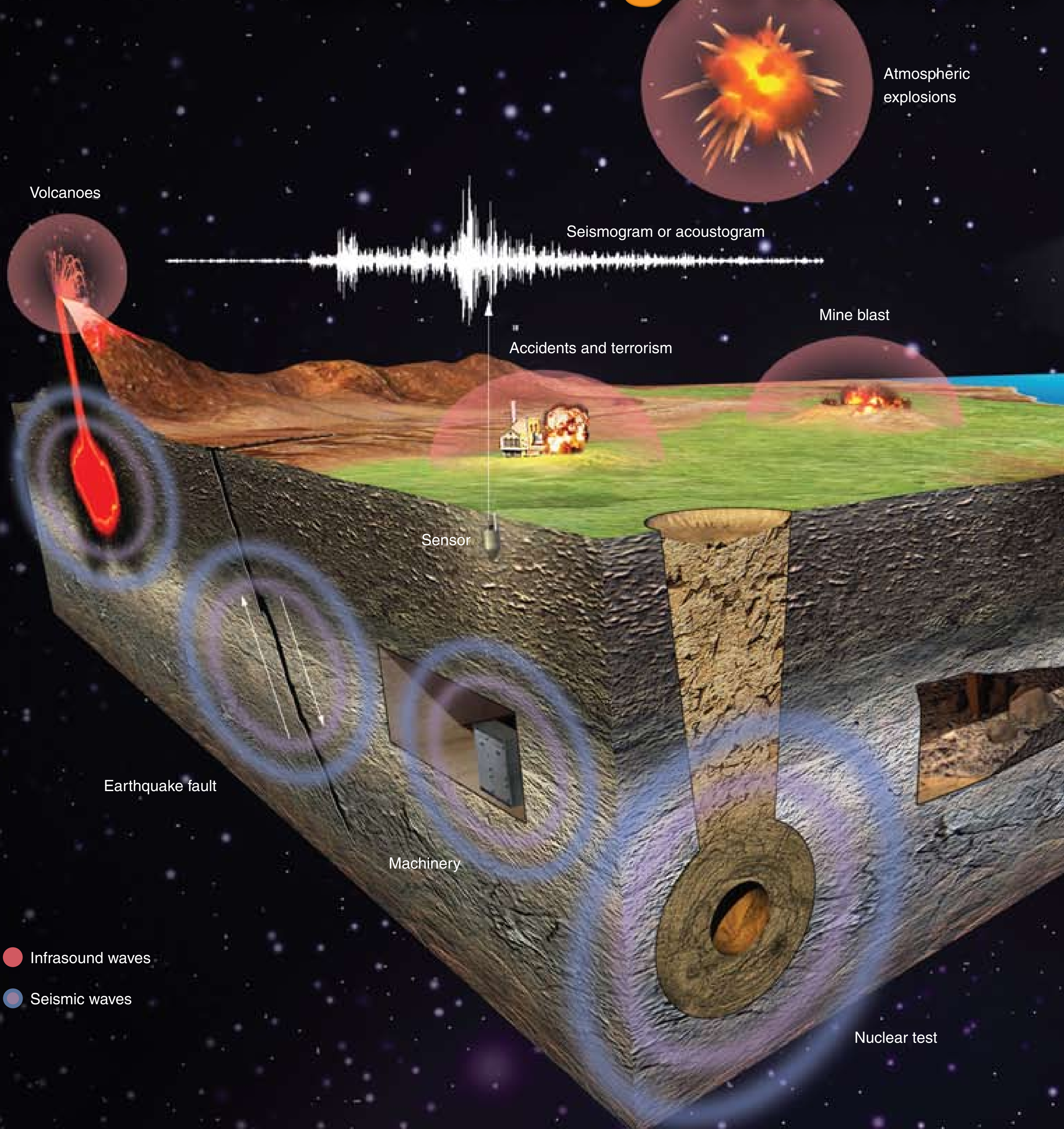
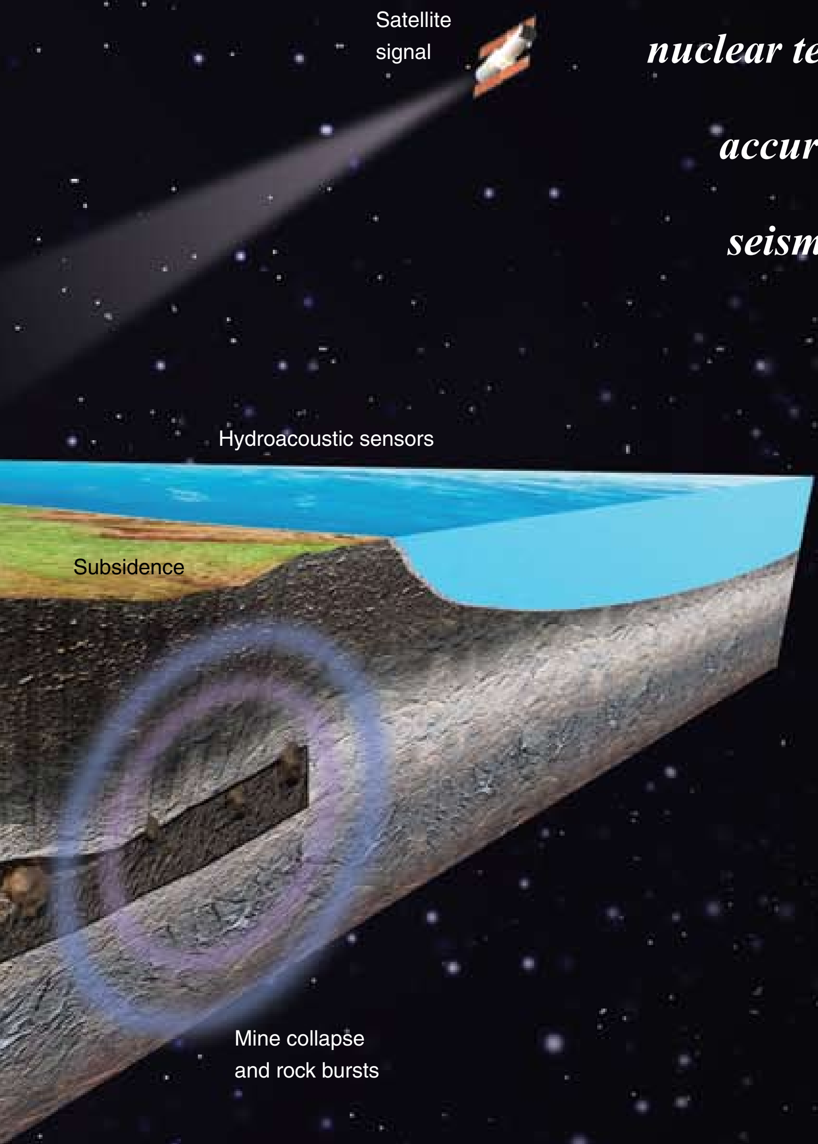
Sleuthing Seismic



Signals

Monitoring the world for clandestine nuclear tests requires accurate forensic seismology tools.

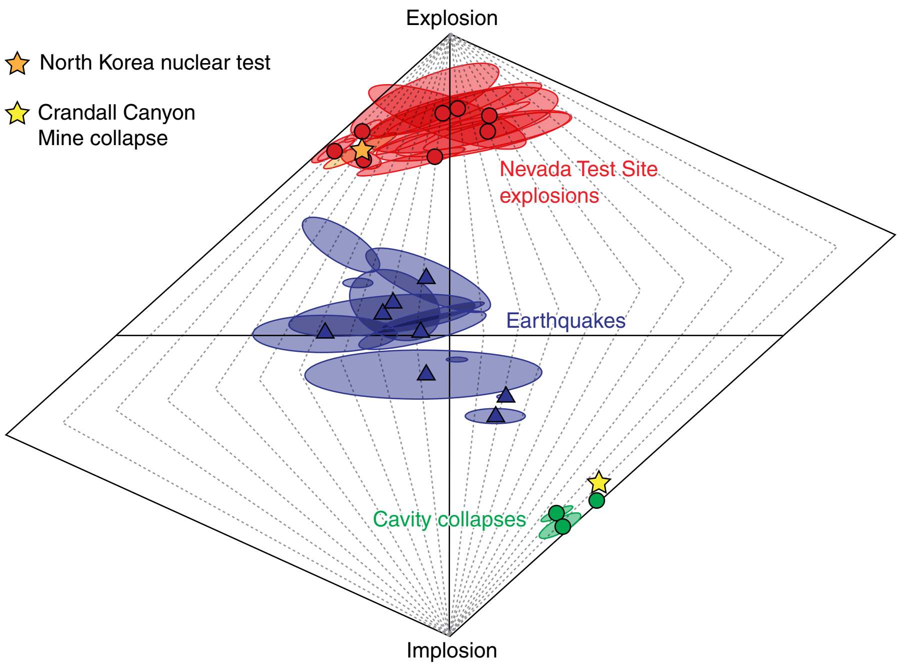


This cutaway view through Earth's subsurface shows many of the disturbances recorded by sensors worldwide.

AN earthquake, a nuclear test, and a mine collapse all cause seismic disturbances that are recorded at monitoring stations around the world. However, these three types of events produce very different ground motions at their source. Earthquakes are caused by sideways slippage on a fault plane, while underground nuclear explosions push outward in all directions. A mine collapse is a massive vertical roof fall.

Lawrence Livermore is at the forefront of research to more accurately distinguish nuclear explosions from the rest of Earth's never-ending seismic activity, including earthquakes large and small, volcanoes, and waves crashing on shore. The Laboratory's work was unexpectedly put to the test following the August 2007 collapse of the Crandall Canyon coal mine in Utah, which killed six miners. Ten days later, another collapse killed three rescue workers. Both events were recorded on the local network of seismic stations operated by the U.S. Geological Survey (USGS) as well as on the USArray stations, which are part of EarthScope, a program funded by the National Science Foundation. There was considerable contention about whether the initial magnitude-3.9 event was caused by an earthquake or a collapse.

At the time, Livermore seismologists were working with colleagues from the University of California at Berkeley on a waveform-matching technique to distinguish among nuclear explosions, earthquakes, and collapse events. This technique compares seismograms produced by computer modeling with recorded data at local to regional distances (from 0 to 1,500 kilometers) for periods of 5 to 50 seconds. Livermore's analysis of the August 2007 seismograms pointed to a collapse rather than an earthquake. The important result for the Laboratory team



Various kinds of seismic events can be grouped on a source-type, or Hudson, plot based on their ground motion. A perfectly symmetric underground explosion would appear at the apex of the plot. By analyzing the seismic waves produced by the disturbance that rocked the Crandall Canyon Mine in Utah in August 2007, Laboratory seismologists determined that the event was an implosive tunnel collapse, not the sideways slippage of an earthquake.

was being able to identify the Crandall Canyon event from its seismic signature despite its small magnitude.

Livermore's seismological research is part of the Department of Energy's support for the U.S. National Data Center in the area of nuclear treaty verification. (See the box below.) The team's experience with the Crandall Canyon Mine has given the Livermore seismologists even greater confidence that they can identify a relatively small nuclear test using the same technique.

Ground-based monitoring of nuclear explosions based on seismic data relies on understanding the fundamentals of ground motion from a high-energy nuclear explosion, the shock waves that propagate near the explosion source, and the subsequent waves traveling away from the source at longer distances. A full understanding is only possible if researchers consider this motion in terms of the geology and topography near the source and surrounding it for many kilometers. For more than 10 years,

Monitoring the Comprehensive Nuclear Test Ban Treaty

The U.S. ceased nuclear testing in 1992 in anticipation of the acceptance of the Comprehensive Nuclear Test Ban Treaty (CTBT). In 1996, President Bill Clinton and many other heads of state signed this multilateral treaty to prohibit all nuclear testing. Although most signatory countries ratified the treaty, the U.S. did not, and several countries required for the treaty to enter into force did not sign it. Expectations are high that the administration of President Barack Obama will reevaluate the CTBT's role in nonproliferation policy.

Although the CTBT is not in force, signatory countries and the U.S. are active participants in the International Monitoring System, which is overseen by the International Data Centre in Vienna, Austria, an organization established specifically to verify the CTBT. Every country supporting the system has a national data center. Livermore provides research and development support to the U.S. National Data Center at Patrick Air Force Base in Florida, which is responsible for U.S. nuclear test monitoring and international treaty verification.

The International Monitoring System comprises a worldwide network of 337 sensitive monitoring stations and laboratories to detect nuclear explosions. Seismic stations anchored to bedrock record underground elastic waves, infrasound stations collect acoustograms from low-frequency sound waves aboveground, hydroacoustic stations in the oceans record underwater sound waves, and radionuclide stations measure airborne radioactive gases or particles. More than 230 of the recording systems now send data to the International Data Centre on a provisional basis. This unique network is designed to detect nuclear explosions anywhere on the planet—in the oceans, underground, or in the atmosphere.

After the treaty enters into force, the signatory countries will have the role of identifying an event as a violation. The treaty also specifies several ways to resolve concerns about suspicious events, from consultation and clarification through a protocol that could lead to on-site inspections.

Laboratory seismologists have used available seismic data to develop and verify their one- and two-dimensional (1D and 2D) regional Earth models and calibrate the dozens of seismic monitoring stations around the world, thereby ensuring that new algorithms properly account for regional geologic characteristics. With expanding supercomputing capabilities at Livermore, 3D seismic models can include more realistic geology for more accurate calibration.

Seismology group leader Artie Rodgers in the Physical and Life Sciences Directorate and others are building on identification techniques first developed during underground nuclear experiments conducted by Lawrence Livermore and Los Alamos national laboratories at the Nevada Test Site. As part of this effort, Rodgers works closely with seismologist Bill Walter, program leader for ground-based nuclear explosion monitoring in the Global Security Principal Directorate.

North Korea Tests

The most recent nuclear test took place on October 9, 2006, when the Democratic People's Republic of Korea—North Korea—detonated a nuclear device. USGS and other organizations worldwide focused on analyzing seismic data from the test. Their aim was to quickly find the location—the epicenter, as it were—of the explosion and measure its size.

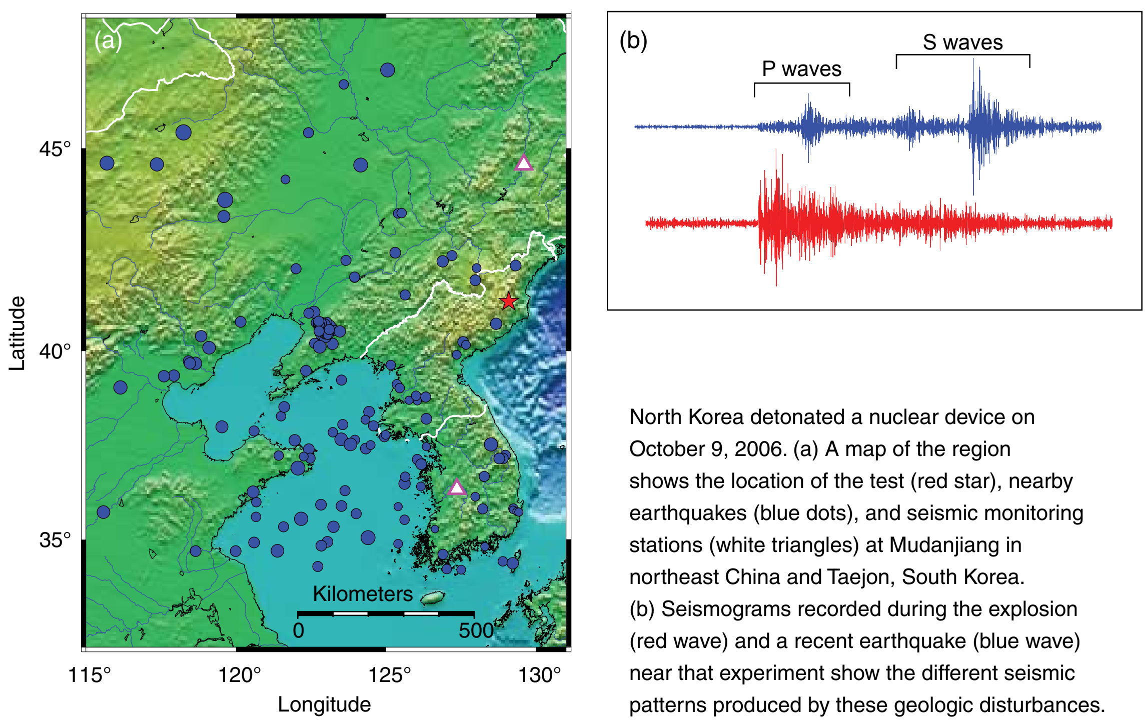
Livermore seismologists also analyzed data shortly after the magnitude-4 event but with a different purpose. The last nuclear experiments had been conducted eight years earlier in India and Pakistan. The North Korea test offered a rare source of valuable new data recorded at the seismic monitoring stations nearest North Korea, which the team could use to test its regional models and various calibration algorithms.

Detecting and Locating

Distinguishing an earthquake from a nuclear event requires a close examination of the seismic waves. Such waves fall into two major categories: surface waves, which move along Earth's surface, and body waves, which move through Earth and bounce off structures inside. Body waves may be primary (P) or secondary (S). Seismic P waves are compressional waves, similar to sound waves in the air. S waves are shear, or transverse, waves, similar to those that propagate along a rope when one end is shaken. Underground explosions radiate P waves in a relatively symmetric spherical shape. Earthquakes, which result from plates sliding along a buried fault, strongly excite the transverse motions of S waves, producing a distinct radiation pattern. Explosions thus show strong P waves and weak S waves. Earthquakes, in contrast, typically show weak P waves and strong S waves.

But this information alone is not foolproof because the structure of Earth imparts an imprint on the signal. One way to quantify the difference between these seismic disturbances is to determine the ratio of P-wave to S-wave energy measured from the seismograms. Explosions should have higher P:S ratios than earthquakes.

Recent Livermore work led by Walter sought to clarify the characteristics of



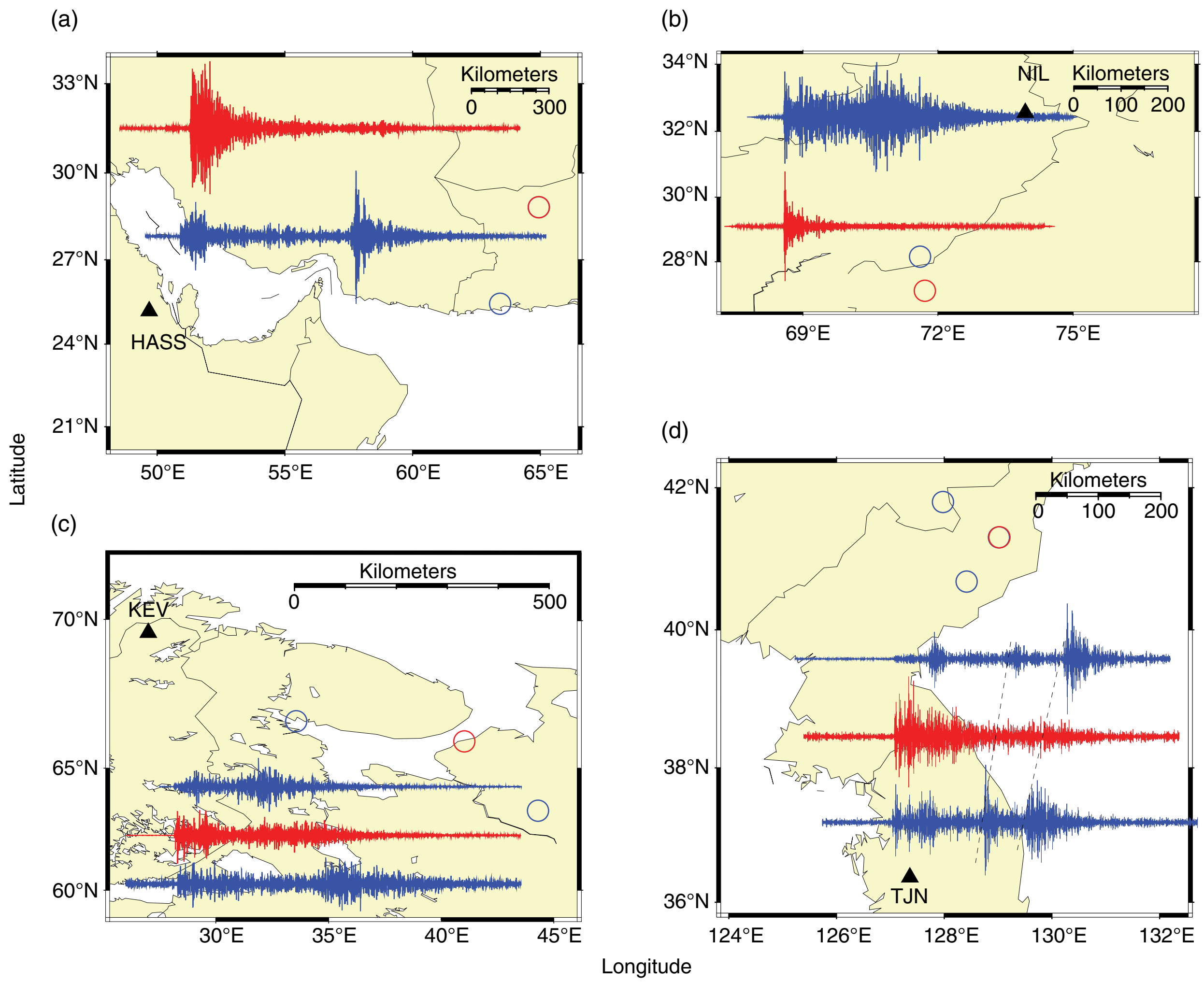
North Korea detonated a nuclear device on October 9, 2006. (a) A map of the region shows the location of the test (red star), nearby earthquakes (blue dots), and seismic monitoring stations (white triangles) at Mudanjiang in northeast China and Taejon, South Korea. (b) Seismograms recorded during the explosion (red wave) and a recent earthquake (blue wave) near that experiment show the different seismic patterns produced by these geologic disturbances.

the P:S ratios that distinguish nuclear weapons tests from other tectonic activity. By examining regional amplitude ratios of ground motion in a variety of frequencies, his team empirically demonstrated that such ratios indeed separate explosions from earthquakes. The researchers used closely located pairs of earthquakes and nuclear explosions recorded at monitoring stations at or near the Nevada Test Site; Novaya Zemlya and Semipalatinsk, former Soviet Union test sites; Lop Nor, China; India; Pakistan; and the North Korea test.

"At high frequencies, above 6 hertz, the P:S ratio method appears to work everywhere we looked," says Walter. "Explosions have larger P:S amplitude values." For example, a test in India on May 11, 1998, compares well with the October 9, 2006, North Korea test.

However, west of Pakistan, in the tectonically complex Middle East, seismogram analysis becomes more complicated. S waves attenuate, or lose energy, more rapidly in regions that are geologically complicated and seismically active. Seismograms from these areas tend to have larger P-wave amplitude relative to their S-wave amplitude. As a result, earthquake signals may look like those from an explosion. Because of these wave propagation effects, Walter's team applied a tomographic technique to measure the highly variable attenuation of S waves in the Middle East.

Tomography is a mathematical operation that uses variations in the waves passing through a material to construct an image of the material's structure. For



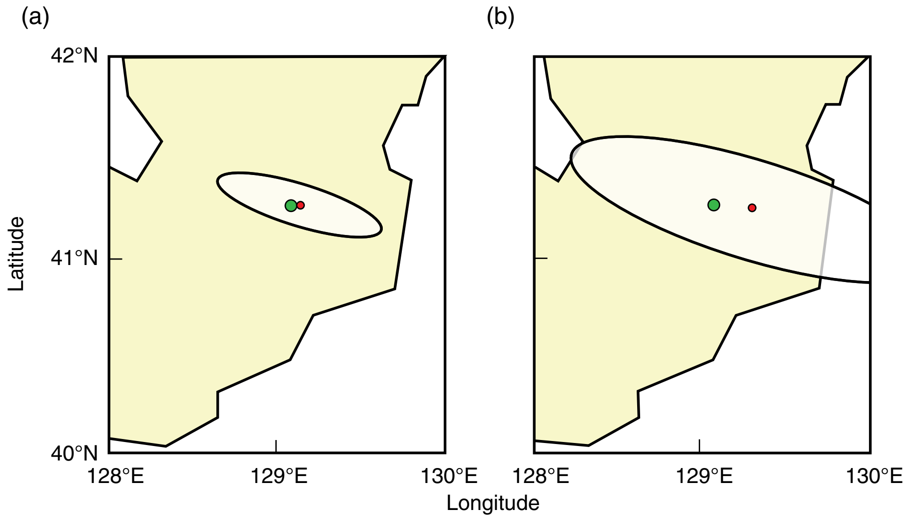
At frequencies of 6 to 8 hertz, nuclear explosions (red waves) consistently have larger ratios of primary- to secondary-wave amplitude than earthquakes (blue waves). Data sources are (a) Pakistan, (b) India, (c) Agate test in the former Soviet Union, and (d) North Korea. Circles indicate event epicenters. Triangles are seismic recording stations.

example, a medical tomography scan uses variations in the waves of x radiation transmitted through the body to produce an image that a radiologist can analyze. Tomography of Earth uses seismic waves to generate comparable images of Earth's inner structure.

The tomographic technique developed by Walter's team models structural deformation based on the attenuation occurring as S waves propagate through different geologic media. Even with the precise algorithms in this tomographic attenuation method, however, some known earthquakes have P:S ratios that look like those of explosions. "We expect that analysis of ground motion at higher frequencies will help us better understand and use this method," says Walter. "But we have only recently had the computational power we need to model high frequencies in 2D and 3D Earth models."

Pinpointing the location of a test is as challenging as distinguishing it from an earthquake. The site of a seismic event is determined by measuring how long seismic waves take to get from the event to the various monitoring stations. Earth's crust and mantle are not homogeneous, however, so velocities through them vary. "Travel-time calculations over long distances can be accurate because the variations tend to average out," says Walter. "But over shorter distances—less than 2,200 kilometers—the 1D, radially symmetric models commonly used in monitoring systems today are prone to error."

At the time of the North Korea nuclear test, a collaborative team led by deputy program leader Steve Myers was working on a new velocity model. The Seismic Location Baseline Model—developed by researchers from Lawrence Livermore, Sandia, and Los Alamos national laboratories; the U.S. National Data Center; and Quantum Technology Sciences,



(a) Livermore's Seismic Location Baseline Model predicts the location of the 2006 North Korea nuclear explosion much more accurately than (b) global, one-dimensional models, which until recently were the standard for determining explosion location. Red dots show the event location predicted by each model, and green dots indicate the actual epicenter. Ellipse area: (a) 1,552 and (b) 8,343 square kilometers.

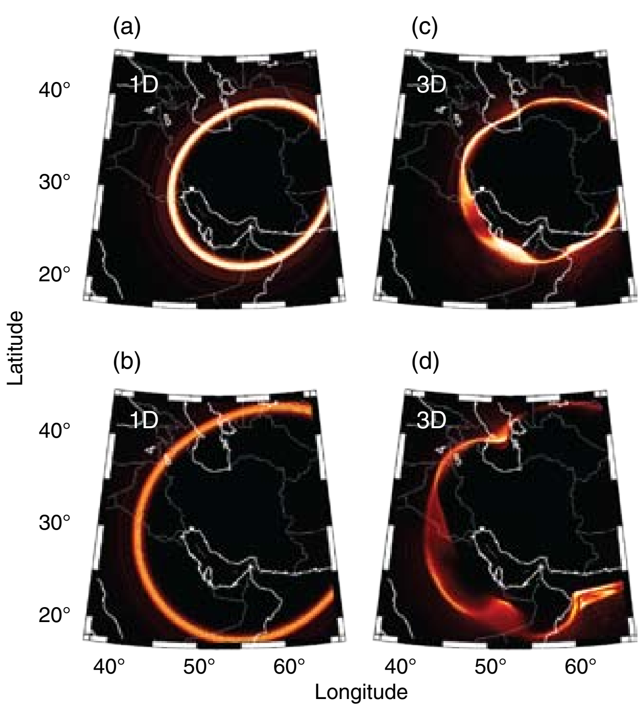
In 2002, Livermore seismologist Artie Rodgers (center) and colleague Cindy Lersten (right foreground) from the Department of Energy worked with a team in the United Arab Emirates to install the country's first seismic monitoring station.

Inc.—has the potential to become the standard for regional travel-time prediction. Not only does the model capture the effects of the 3D Earth, but it also can be used in a real-time monitoring system because it is so efficient computationally. "We expect the National Earthquake Information Center, which is part of the USGS Earthquake Hazards Program, to begin evaluating our model sometime this spring," says Myers.

One reason the Seismic Location Baseline Model can so accurately predict the travel time of seismic waves is that its tomographic imaging techniques better capture the structure of Earth in 3D. These techniques use travel-time data to predict geologic structure based on variations in seismic-wave velocity. "We combed through large databases of seismic measurements for high-quality data," says Myers, "and applied tomographic methodology to modify the model to better predict measurements." The Seismic Location Baseline Model can currently resolve Earth structure with a lateral dimension of 100 kilometers. Ongoing efforts include increasing the model's resolution in areas where data are available and extending the model's capabilities to predict all seismic phases.

Focus on the Middle East

In 2002, Rodgers led the team that installed the first seismic monitoring stations in the United Arab Emirates, around the epicenter of an earthquake that occurred in a normally aseismic area. New seismic stations in the Emirates and other Middle Eastern countries allow local seismologists to prepare for future earthquakes by indicating where small earthquakes occur and helping define seismically active faults. In return, Laboratory researchers use data from these and other stations to learn about earthquakes and Earth's structure. Lawrence Livermore is the National Nuclear Security Administration laboratory responsible for seismic calibration of the Middle East for nuclear treaty verification. Livermore researchers work with scientists in many Middle Eastern countries to gather and evaluate ground-motion data.



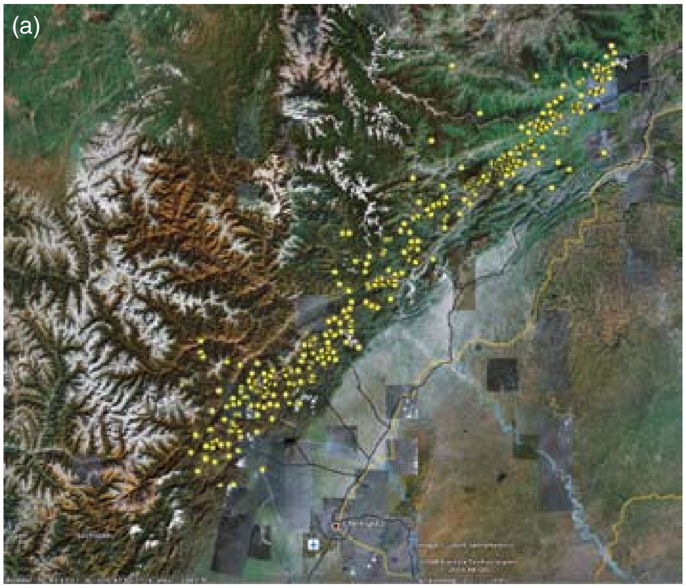
The latest three-dimensional models capture vertical ground displacement far more accurately than one-dimensional models. These images show the ground motions for (a, b) one- and (c, d) three-dimensional models at different times after an event. Comparison with recorded ground motions indicates that the three-dimensional model better predicts the observed behavior.

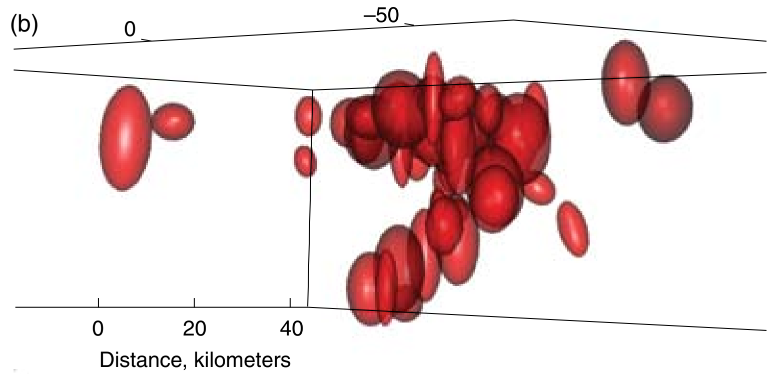
Rodgers serves as the Laboratory's representative to an organization called the Reduction of Earthquake Losses in the Extended Mediterranean Region, which was established by USGS and the United Nations Educational, Scientific, and Cultural Organization. He and Livermore's Rengin Gök and Michael Pasyanos attended the most recent meeting in Istanbul, Turkey, in May 2008, which included scientists from Cyprus, Egypt, Iran, Israel, Jordan, Kuwait, Lebanon, Libya, Oman, the Palestinian Authority, Saudi Arabia, Turkey, the U.S., and Yemen.

Gök represents the Laboratory in a multinational data exchange agreement with Turkey, Azerbaijan, and Georgia, countries in an area with a high potential for earthquakes and concerns about nuclear proliferation. As part of this agreement, seismologists in the three countries share their ground-motion data with Livermore researchers, who then analyze the data and add them to the store of information for calibrating monitoring stations in the Caucasus region. Gök notes that this particular agreement will end in late 2009, but she is already at work on proposals for similar international scientific exchanges in the region.

Seismic Simulations Go Parallel

With BlueGene/L, one of the world's most powerful supercomputers, Livermore's seismologists are developing much improved 3D simulations for detecting nuclear detonations. Says Walter, "Much 3D seismic modeling requires





(a) Seismic data on the aftershocks (yellow dots) of the May 2008 magnitude-7.9 earthquake in Sichuan, China, were used in Livermore's Bayesloc method to produce (b) a cross section of the fault plane viewed from the southwest, revealing its structure.

the high-performance, massively parallel computing capability that we have here at Livermore." Advanced computational power allows for greater numerical resolution of simulations at higher frequencies and covering larger regions. These simulations are especially important for evaluating seismic activity that occurs in parts of the world where earthquakes and other natural ground motion are rare.

Rodgers leads a team of Livermore seismologists, mathematicians, and computational experts who have set the stage for simulating wave propagation in realistic 3D geology. To date, they have focused on three areas: wave propagation within less than 1,500 kilometers of an explosion source, geology and topography of Earth, and nonlinear hydrodynamics of shock waves. For regional-distance simulations, the team compared observed waveforms at various monitoring stations with simulated ones and compared 1D models with 3D models.

Livermore applied mathematician Anders Petersson led the development of an open-source code called WPP for simulating the propagation and anelastic attenuation of seismic waves. The WPP team is extending the code to handle realistic topography, which is important to accurately simulate the propagation of shorter waves associated with higher frequencies. Petersson's team has developed a hybrid numerical technique that combines the complex calculations necessary to capture the effects of topography with an efficient scheme for subsurface geology.

The team is also coupling WPP to GEODYNE, a code that handles nonlinear hydrodynamic wave propagation. Nonlinear hydrodynamic behavior results from the high energy density of chemical and nuclear explosions, which causes vaporization, cavity creation, and other phenomena before stimulating elastic seismic waves. Modeling the near-source phenomena is key to improving amplitude and yield estimates and understanding the generation of S waves.

Yet another team, led by Myers, has developed a Markov Chain Monte Carlo probability method called Bayesloc for locating seismic events. According to Myers, "Bayesloc simultaneously locates a selection of events, evaluates data quality, and assesses the transit time of seismic waves from the source to each monitoring station."

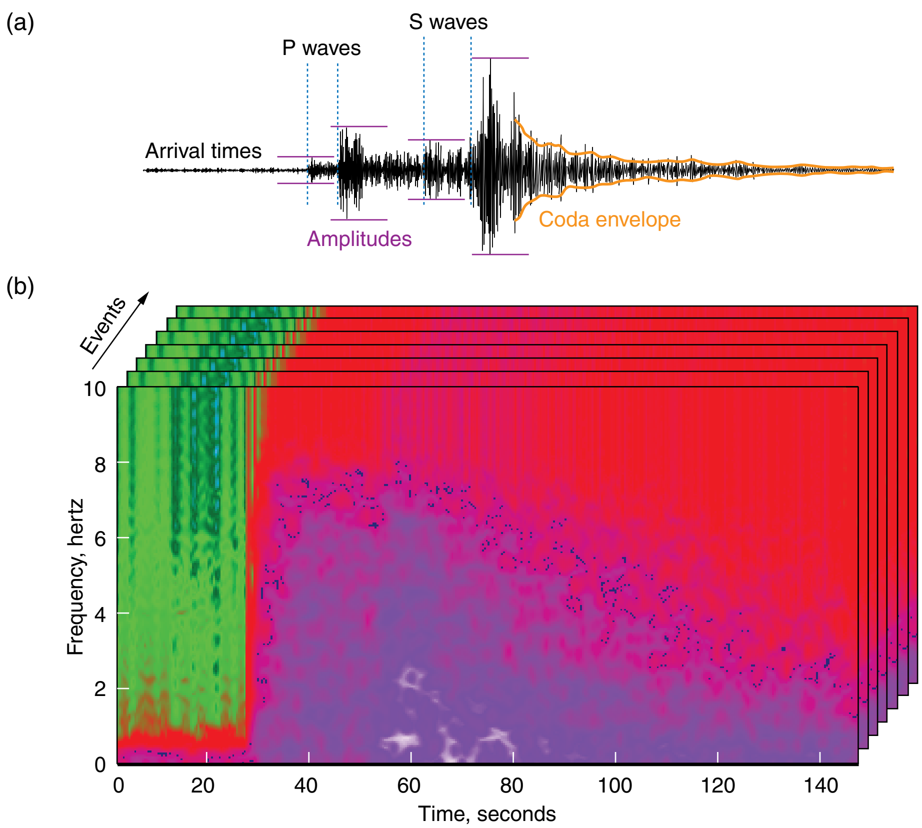
Myers and his team used Bayesloc to pinpoint the aftershocks following the May 12, 2008, magnitude-7.9 earthquake in Sichuan, China. "Locating the aftershocks allowed us to identify the fault plane, which is almost as long as the distance between Los Angeles and San Francisco," says Myers. "The initial quake and its aftershocks thrust the mountainous shelf over the Sichuan Basin." That project did not require massively parallel supercomputers, but the team's next project will. "We plan to simultaneously locate all earthquakes for which we have data," says Myers. "Then when a new quake happens, it can be located in the context of all previous events."

Walter leads the effort to further develop the technique that worked so well in identifying the source of the Utah mine collapse. "We are expanding to a broader range of frequencies and to a different kind of matching," he says. In current seismological practice, the seismogram is deconstructed manually into a series of arrival times, or "picks," for locating the event. Manually selected amplitude measurements also provide information about the event type and its size or yield. However, this method uses only part of the waveform.

A proposed future practice is to convert the entire seismogram to a template, eliminating manual picking and making full use of time–bandwidth data. The template for an event could then be compared with those of previous events or, if no prior event has occurred in a region, to model-based templates. "This new process will allow us to immediately locate, identify, and characterize events relative to all prior events or our models," says Walter. "In addition, we can more easily automate the processing."

This is an exciting time for Livermore seismologists. With the advent of a fully 3D simulation capability, greater automation for analyzing seismic events, and renewed interest in the Comprehensive Nuclear Test Ban Treaty, ground-based nuclear test monitoring research is entering a new era.

—Katie Walter



Livermore seismologists are exploring ways to replace (a) the current practice of manually analyzing discrete parts of a seismogram, such as times, amplitudes, and envelopes of specific waves, with (b) conversion of the entire seismogram into a template that can be compared with other event templates.

Key Words: Comprehensive Nuclear Test Ban Treaty (CTBT), Crandall Canyon Mine, explosion monitoring, International Monitoring System, nuclear testing, nuclear treaty verification, seismology.

For further information contact Bill Walter (925) 423-8777 (bwalter@llnl.gov).